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Simultaneous multiuser demodulation based on digital array processing

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The use of antenna arrays to increase the efficiency of a communication link is studied. This work addresses a technique to solve the collision problem that takes place when various users ask simultaneously for access. It consists in a Time Reference Multi-beamformer/conformer system (TRM), which is implemented on a two-stage architecture. Taking advantage of the statistical independence of the impinging references and of the spatial diversity introduced by the array, the goal is the simultaneous demodulation of users, regardless their co-channel nature. The results show the increased system capacity for the specific case of a BPSK communication link. Other desirable features as robustness to calibration errors or good performance of the multiuser system both in adquisition and tracking are illustrated.

1.Two-stage architecture for multiple beamforming / Combining.

The application of Time Reference Beamforming or Combining (TR) [1] techniques in the past years have revealed that, in a communication context, array processing brings in improvements in the final system performance. The major feature that TR systems present is that they offer the possibility of spatially descrimination of users. TR systems just need some knowledge of the transmitted signal structure in order to properly combine the signals received by the sensors for maximizing the SNIR. Thus, any further knowledge of the scene, as for instance array calibration or source location, is needed; just the local regeneration of the reference at the receiver is crucial not to properly equalize the channel.

The existing alternatives for reference framing are either by Frequency Multiplexing (FDMA), Time Multiplexing (TDMA) or Code Multiplexing (CDMA) TDMA has the advantage over FDMA that it may cope with the case of wideband interferences, being quite sensitive, however, to pulse radar and burst transmission systems. CDMA systems get round both problems and allow access of various users in the same time-frequency slot. However, CDMA requires more complexity and higher thresholds for synchronism units. Thus, code framing is not allways the most suitable for low cost receivers (i.e. mobile recievers).

This article sets out to design a high efficiency multiple access Time Reference system that may cope with simultaneous users just with little additional complexity. Specifically, this paper addresses the worst situation, when simultaneous access in the same time-frequency slot takes place. Neither code nor modulation will differenciate the users among them. On these bases, the first task at the receiver is to identify each user (i.e. solve the collision problem); next, once the sufficient SIR is obtained, the receiver will be able to form a dedicated beam for each user. The solution that is put forward by the authors in this paper (figure1) has been obtained by envisaging the problem from the Kolmogorov's neural network mapping theorem [2]: from a two-stage architecture standpoint. A *first stage* will deliver each of the impinging references with enough SNIR in order for a *second* reference regenerating (R.R) *stage* to identify them without problems. For each user, the RR stage will elliminate the contaminating noise in order for the multiuser receiver to build one beamformer that steers at each user and is adapted to

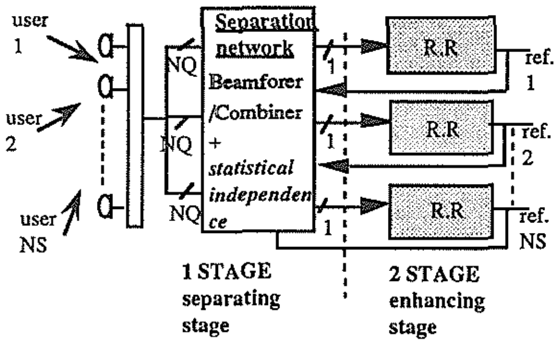

Figure 1. Proposed two-stage architectue for multiple access Time Reference

the scenario.

The final architecture will combine array processing, High Order Statistics (HOS) [3] and demodulation techniques. By means of beamforming techniques, array processing will allow both spatial descrimination of users and lower SNR requirements. On the other hand, HOS will be the major tool to enable the identification of users in a first accessing time and to surveille the proper tracking of users in a subsequent time. HOS will be a consequence of the *statistical independence* condition that the receiver will impose on the user signals. Finally, demodulation techniques will reduce the noise in order for the global communication system to attain the required bit error rate (BER). It is important to note that the final performance will depend on the interaction among each of the three mentioned elements. The more they would cooperate, the better they good perform [4].

In [4], the authors address the problem of increasing the capacity of a FDMA system by simultaneous tone demodulation. This work is presented as a step further, which aims a general simultaneous demodulation scheme. Next section will widely discuss the relevance of the statistical independence assumption in the previous outlined design for an advanced communication receiver. Specifically, statistical independence is the basis for the design of the first separating stage, which will be of crucial importance to avoide collision and which will keep on with the self-calibration philosophy that characterizes Time Reference systems.

2. First stage: blind user separation.

The problem known as blind separation of sources [3] opens new prospects in many fields like communications and

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antenna processing. It can be simply formulated as follows: after propagation, the NQ signals x_i received on an array of NQ sensors are linear mixtures of NS sources s_i in thermal noise v

$$x = A.s+v = [a_1\ a_2 \ldots a_{NS}].s+v \quad (1)$$

The objective is to reconstruct the individual sources which are supposed zero-mean and statistically independent. The only knowledge is the observation of the mixture x (hence the frequent epithet *blind*). Several approaches have recently been proposed to solve this problem, by taking a linear system:

$$y = W.x = [w_1^H; w_2^H; \ldots ; w_{NS}^H]x \quad (2)$$

and seeking for an adequate matrix **W** such that y has independent components. Such a matrix is called "separating matrix".

This requirement has no unique solution. If y has independent components, the same property holds for the vector **P.D**.y for any permutation matrix **P** and any regular diagonal matrix **D**. Therefore, one has to find a matrix W such that

$$W.A=P.D \quad (3)$$

Among the various existing techniques, we recall the initial work of Jutten and Herault [5], which is going to be commented in next sub-section.

2.1. Neural Network architectures

In order to simultaneously separate the sources $s_i(t)$ from signals xi(t), the authors Jutten and Herault proposed in 1985 a solution, derived from a neural approach. Their neural architecture fully described in various references [5], stands out because of its competitive behaviour. If the inhibition weights w_{ij} are properly designed, the separated signals at each branch will then be the desired source signals. Before getting into the weight design we will remark one main feature: the recursive nature of the structure. The IIR structure confers faster convergence to the network. However, the reader should note that the fast convergence will always trade off with stability due to the close loop that is involved in the feed-back. Additionally, the inherent delays this network introduces must be taken into account in order to attain a successful performance, especially when working with digital signals. One way out of this problem is to utilize instead the feed-forward net counterpart.

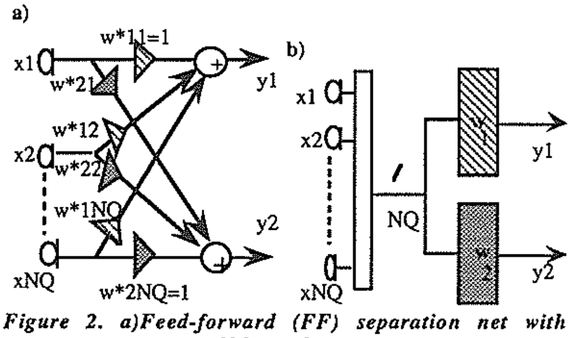

Figure 2. a)Feed-forward (FF) separation net with more sensors NQ than sources (two); b)interpretation as beamformers/combiners

As digital array processing is of main concern in this work, the authors will base the design on the FF structure. Figure 2.a oultines the resulting architecture for the case of using more sensors than sources to separate. A straight forward interpretation of this net is to consider it as two beamformers. This perspective connects with the cross-coupled boot-strapped interference canceler proposed by Y. Bar-Ness in [6]. Bar-Ness originally studied the possibility of building a blind interference canceler, thus without need of a reference signal. Next, a suitable adaptive design for the inhibition weights is going to be presented.

2.2. Inhibition learning

This work aims to find a reliable adaptive solution for the blind identification of users. Hence, in order to find a learning rule for the inhibition weights **W**, first an appropiate cost function ϕ has to be designed. Blind identification techniques rely on the assumption of mutual independence of the source signals received at a given time. Based on the approach of Jutten/Herault. The authors study in [4] to impose on the output of the separating network the criteria $\phi 1$, equated in (4)

$$\phi 1=|E\{y1.y2\}|^2\Big|_{min} \qquad \phi 2=cum\{|y1|^2.|y2|^2\}\Big|_{min} \quad (4)$$

However, in presence of Gaussian noise, this cost function results in a quite low performance. In consequence, to overcome this shortcoming, the authors proposed the cumulant criterion $\phi 2$, which has been parallely developped by Jutten/Herault. For the case under scope of two signals that are circularly distributed (i.e. BPSK sources), the minimum of $\phi 2$ is equivalent to diagonalizing the forth-order cumulant matrix of the outputs y. Thus, there is a link to the well-developped eigenbased techniques [7].

Before getting into the features of criterion $\phi 2$, we remark that our interest concentrates on the separation of two users. In the application under scope, the probability of encountering a more-than-two user collision is low. Moreover, in accordance to the Shannon's theorem an increasing number of simultaneous users is only possible if the SNR at reception augments. However, in the present work, we are going to consider the more usual situation of low SNR scenarios.

In the sequel, the authors will discuss the robustness of the forth-order criterion $\phi 2$, which is the key of the successful performance of the separation net. By resorting to some cumulant properties and considering eq.(1,2), the cost function $\phi 2$ can be formulated as in eq.(5)

$$\phi 2=|w^H{}_1.a_1|^2.|w^H{}_2.a_1|^2 cum_4 s_1+|w^H{}_1.a_2|^2.|w^H{}_2.a_2|^2 cum_4 s_2 \quad (5)$$

As we are interested on users who issue signals of equal modulation features, the source signals s_i have the same sign of kurtosis (i.e. $cum_4 si$). Thus, $\phi 2$ will be either positive definite or negative definite. For this reason, we search for the zeros of $\phi 2$. They will be the global extrema of $\phi 2$ if they null the first derivative of the cost function and make the third derivative either positive or negative. From eq.(5) it is straight forward to obtain that **W.A=P.D** is the solution for the weights that fullfils the global extrema conditions. Additionally, as $\phi 2$ depends in a quadratic form on the separating weights wi, it can also be concluded that there is no local extrema. In consequence, the designed cost function is suitable for simple but effective gradient adaptive algorithms.

The learning rule for the weights is obtained as

$$w_{ij}(n+1)=w_{ij}(n)+\mu i_{nomr}.cumulant\{xj.y^*_i/yj/^2\};\ i\neq j$$

$$\mu_{inorm}=\frac{\alpha}{E\{x^H.x./yj/^2\}} \qquad (6)$$

with w_{11} and w_{2NQ} set to unity in order to avoid the trivial solution in the min/maximization of $\phi2$. The value of μ has been computed to assure good convergence irrespectively of the signal power.

A more detailed description of the proposed inhibition learning rule in eq.(6) can be found in [8]; in the sequel, we will just concentrate on its importance for the design of a Multiple Access Time Reference system. Next section is going to present in which way the whole two-stage architecture (figure 1) is specifically implemented for BPSK references.

3.Time Reference Multiuser system

For each Time Reference system and application, interference or collision will originate under different circumstances. In frequency framing systems with frequency reuse, whose link access is performed by a single unmodulated carrier confined in a specific processing bandwidth, collisions will take place because of co-channel interference. The Multiple Access system is then expected to cope with such situation at the accessing time. In [4], the authors resorted to the two-stage receiver (figure 1) in order to cope with the mentioned interference /collision problems, thus to increase the system spectral efficiency.

Unmodulated reference sytems are the most suitable for low complexity receivers, however, their spectral efficiency is low when compared with other framings. Next section will overcome some of the shortcomings that unmodulated carrier TR presents at the expense of convergence rate for access and complexity: the reference will now present an specific modulation.

3.1. Time Reference Systems with modulation framing

The increasing demand for mobile communication services without corresponding increase in RF spectrum allocation motivates the need for new techniques to improve spectrum utilization. This is the case of using BPSK signals as reference for the Time Reference (TR) system. In this case, the reference signal can be inherent to the information message that the user wants to transmit. Therefore, it is not necessary any time or frequency framing to transmit the reference, conferring robustness and velocity to the TR system. The main drawback in the BPSK time reference beamformer is that it needs a more complex reference regenerator (R.R) (second stage) than the one used for frequency framing systems (i.e. phase lock loop). The BPSK signal enhancer should consist of a BPSK demodulator-modulator pair in order to regenerate the noisy received data. The BPSK demodulator would require then rather high Eb/No (greater than about 11 dBs) to offer a Bit Error Rate lower enough to enable a good quality transmission (BER less than 10^{-5}). Moreover, due to the inherent delay that results at the output of a BPSK demodulator, the quick feed-backward HOS separating network is not feasable. The resulting structure is shown in figure 3.

In the inhibition stage, in a feed-forward manner (figure 2), the separation structure will resort to the High Order cost function $\phi2$ formulated in (4) in order to achieve a good reference separation from the received *noisy* signals.

The HOS separating network will make the system

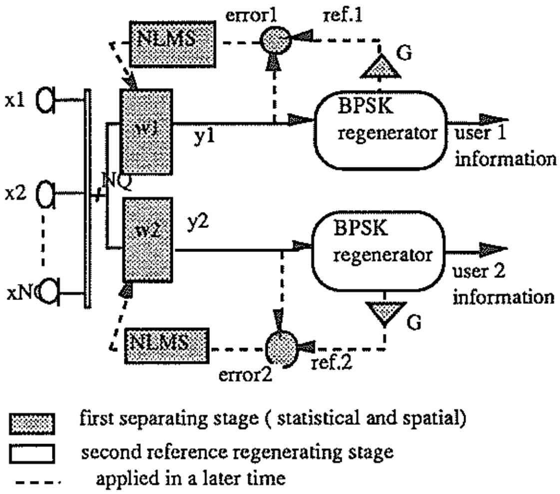

Figure 3. Mutiple Access BPSK TR system (two user case)

start by separating the impinging references. The network should deliver each BPSK reference with the sufficient SNIR for the BPSK enhancer (second stage) to work properly. Once the BPSK references would be regenerated in the second optimization stage, the separating weights could be designed as spatial Wiener filters (dotted line in figure 3).

This section intends to be no more than an example of the more general situation of modulated framed time reference, for which a general separating network has been proposed in section 2.3. The scheme in figure 3 will be easily extended to other modulation systems just by properly changing the second optimization stage.

4. Simulations

An example of the simultaneous demodulation performed in the TR system with BPSK framing presented in figure 3 is shown in figure 4. Figure 4.a first depictes the reception pattern of the HOS separating network W , it introduces the adequate SIR at each branch in order for each TR system to be able to regenerate each of the BPSK signals and build from the

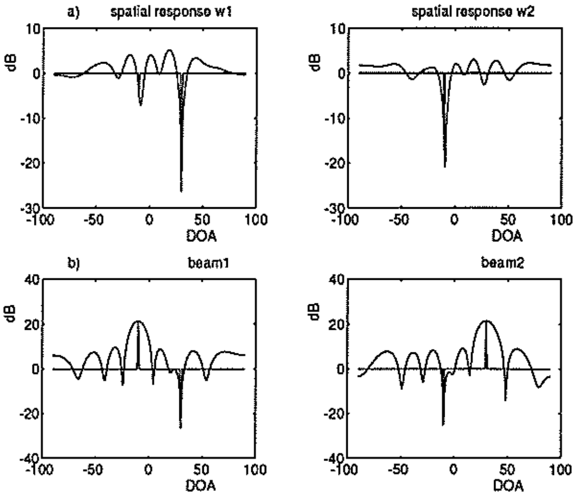

Figure 4.Scene: 2 BPSK signals (SNR:10 dB, elevation: -10º,30º), noise: 5dB, linear array of 8 sensors. a)spatial response of HOS network, b)subsequent TR beam with BPSK reference.

initial HOS weights the final beams plotted in figure 4.b. This beams introduce a higher SNIR in each communication link (SIR=45 dB, SNR=5 dB+10log8).

To bring out the good performance of the separating HOS net used in section 3.1, figures 5,6 plot the spatial response for one of the parallel branches under pretty bad SNR and resolution conditions. In figure 5b and 6b, the corresponding learning curve is shown. As expected in adaptive arrays that are ruled out by gradient techniques, if the number of sensors is increased, not only the ouptut SNR would augment but also, the convergence rate and resolution would be higher. On the other hand, due to the correct normalization of the adaptive algorithm (μnorm), the misadjustment is not increased by the increasing number of sensors.

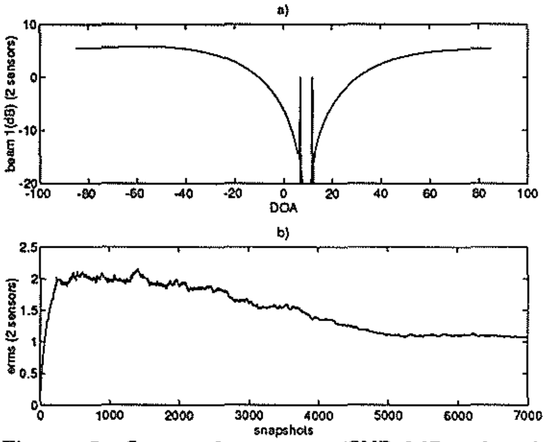

Figure 5. Scene: 2 sources (SNR:2dB, elevation: 7º,12º), linear array of 2 sensors; a)spatial HOS net response; b) learning curve.

Finally, to show the capability of the separating network to adapt to time variant channels, figure 7 depicts the tracking for two moving sources (from 15º to 0º and from 5º to 15º respectively). The slower the movement the better the tracking. Thus, as for instance in case of mobile communications with low fading rates, this separating net will be suitable for surveillance of proper tracking of users. Otherwise, close location of users would cause the beamformers to collapse.

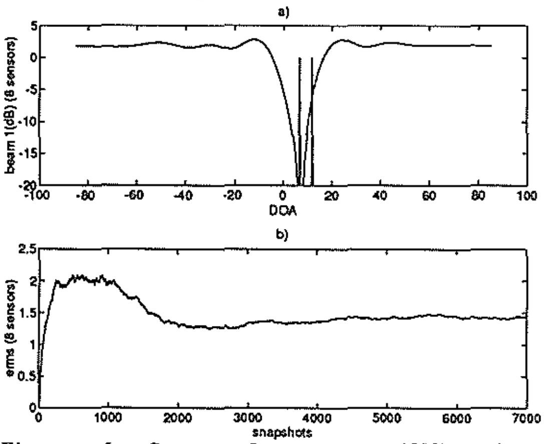

Figure 6. Scene: 2 sources (SNR: 2 dB, elevation:7º,12º), linear array of 8 sensor; a) spatial HOS net response; b) learning curve.

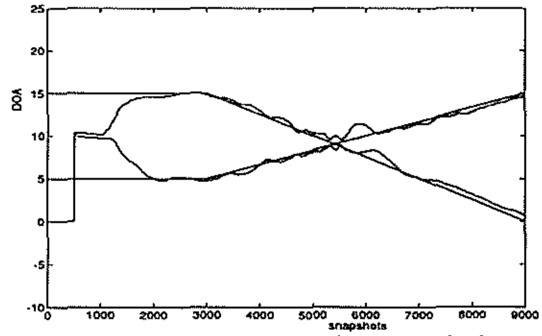

Figure 7. Moving nulling introduced by the separating network due to the two present moving sources (BPSK signals of 2 samp./symb.)

5. Conclusions

The problem of simultaneous demodulation of multiple users who share the same channel and modulation is solved by resorting to a two-stage processing architecture. This general architecture, based on the A.Kolmogorov theorem, resorts to the spatial diversity of the users together with the statistical independence of their sent signals. This architecture integrates novel tools in Signal Processing (HOS, neuromimetic networks,...) and classical existing techniques, as for instance the Wiener filter theory. Therefore, this work further supports our believe in such architecture as one step ahead towards a new filtering concept.

Focussed under the Time Reference Beamforming concept, the results have also been exposed in order to extend them to Optimal Comibining systems.

6. References

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